archives

Back-to-Basics, July 1998

Archives Index | 1998 | July 1998 |

The principles of laser welding

By Leonard Migliore

Laser welding is a powerful, versatile process that joins metals or non-metals at high speed with a very low heat input. Lasers can produce welds in air, in vacuum, in controlled atmospheres, and in pressurized chambers, and this process is easily automated and highly reliable.

Thousands of lasers are used every day to join metallic and non-metallic parts ranging from microscopic electronic components to heavy-gauge pipe; in weld penetrations from 0.1-8 mm. When considering laser welding as a joining process, it is useful to examine its principles, advantages, and limitations.

How lasers weld

According to the American Welding Society, welding is "The localized coalescence of metals or non-metals produced by heat and/or pressure." This definition describes a wide range of processes including soldering, brazing, and fusion welding. Lasers are used for all of these, but this article examines only fusion welding. Soldering and brazing join material with low-melting fillers, while fusion welding is performed by melting some of the workpiece, with or without the addition of filler materials.

There are a large number of fusion welding processes. Most of them, such as gas tungsten arc welding (GTAW) and shielded metal arc welding (SMAW) are appropriate for joining heavy sections. Laser beam welding (LBW) is a precise, low total heat input process ideally suited to automated production.

As indicated in previous articles in this series, laser light may be focused to very small areas. If a 1-kW laser beam is focused to a spot 200 microns in diameter, the irradiance (often referred to as the power density) is 1000 divided by the area of the spot (3.14¥10-8 m2) or 3.2 X106 W/cm2 (For some reason, irradiances are almost always reported in units of W/cm2 even though this isn't a proper SI unit).

This tremendous concentration of power is necessary for the welding process to occur. Laser beams are light beams, and metals are very good reflectors of light. This problem is compounded by the fact that the major industrial laser types emit infrared light, which metals reflect even better than visible light (see Figure 1). As a result, most of the incoming power bounces right back at the source as indicated in Figure 2A. (This, by the way, can damage lasers and lenses.) Because metals are also good conductors of heat, the power that does get into the work is rapidly dissipated away from the spot being heated. The only way lasers can weld metal is by applying so much power that the small fraction absorbed in the work is enough to melt it. This is the

condition shown in Figure 2B, and that's why you need 106 W/cm2.

Keyhole welding

Once the surface melts, everything changes. Liquid metals absorb much more light than do solids, so the heat input suddenly increases, raising the metal's temperature above the boiling point and generating metal vapor (Figure 2C). The pressure of this vapor opens a channel around the laser beam, forming what is called a keyhole.

A fully developed keyhole, shown in Figure 2D, traps almost all of the incident laser power and converts it into heat. Some of the light is absorbed by the vapor, while the rest bounces around inside the channel and delivers energy with each reflection. The keyhole allows lasers to produce welds that are deep and narrow, because power is delivered to the work through the vapor channel. The aspect ratio (depth/width) of keyhole laser welds can be as high as 10:1 but is more commonly around 4:1.

At irradiances above 106 W/cm2, the above events occur within a microsecond in materials such as steel. Keyhole welding is a threshold process: when the irradiance is low, very little power is absorbed. Once the irradiance is high enough to form a keyhole, most of the power is absorbed by the work. Small power changes near the keyhole threshold will cause dramatic changes in the weld.

Conduction welding

One may choose to laser weld without forming a keyhole by keeping the irradiance low. A value of 1-5¥105 W/cm2 will cause surface melting without keyhole formation. This process, called conduction welding, is typically done with Nd:YAG lasers rather than with CO2 lasers. This is because solid metal absorbs more Nd:YAG light than CO2 light. For example, stainless steel absorbs about 25% of incoming Nd:YAG light versus about 5% of CO2 light. When the metal melts, however, it absorbs about 50% of the light at either wavelength. The absorbed power then doubles for Nd:YAG welding, but increases by a factor of 10 for CO2 welding. The sudden change in absorption by an order of magnitude makes CO2 conduction welding unstable; once there is enough power to melt the surface, there is almost always enough to form a keyhole. With a Nd:YAG laser, the absorbed power doubles upon melting, but this leaves a fairly large process window between melting and vaporization. When there is no vapor channel, all the power is absorbed on the surface of the weld; subsurface melting occurs by conduction (hence the name of the process) and convection. Conduction welds are consequently semicircular in cross section with aspect ratios of 1:2 or less.

Setting up for laser welding

It is very simple and straightforward to set up for laser welding: just focus a laser beam on the workpiece where you want it to melt. Figure 3 schematically shows the necessary elements. For keyhole welding, the laser must be large enough to produce 106 to 107 W/cm2 on the work; the power level, of course, is going to be related to the spot size that the focusing optics produce. The spot size should be about 30% of the weld width. It is generally inadvisable to exceed 107 W/cm2 because this will overheat the keyhole, causing ejection of molten material.

Hermetic seals are usually made by making a series of overlapping conduction spot welds from a pulsed Nd:YAG laser. For conduction welding the laser power should be such that the irradiance is 1-5¥105 W/cm2. The laser spot size is set to about the desired weld width, and the laser's pulse duration is set to produce a roughly hemispherical fusion zone. The pulse repetition rate and the travel speed are adjusted so that each spot overlaps the previous one by about 70% of its diameter.

The focusing optic is usually a lens with Nd:YAG and small (<1 kW) CO_2 lasers, but metal mirrors are a better choice with large CO_2 welders. In high-power welds, material is ejected from the keyhole with considerable velocity. Because the keyhole is a narrow tube lined up with the axis of the laser beam, all the particles with enough initial velocity will end up on the optic. The hot metal particles cause irreparable damage to the coatings on the expensive lenses that CO_2 lasers use. Each damaged area absorbs power and heats up the lens; the resultant thermal focusing degrades the spot at the weld and the process goes out of control. At multikilowatt levels, lenses can be destroyed in a few hours of use. Copper mirrors get just as much debris on them as lenses, but they are not damaged by it: the contamination can be removed, and the optic is as good as new.

At the workpiece end, some shield gas is usually applied to protect the weld from oxidization. Argon or helium are the most common choices. Argon is heavier than air so it provides a better shield than helium, but it ionizes easily and has much lower thermal conductivity than helium. This causes a problem with high-power CO_2 welding: The metal vapor emerging from the keyhole is partially ionized, with charged atoms and free electrons. The free electrons absorb some of the laser light, reducing the power available for welding. As the vapor absorbs energy, it heats up, increasing the number of free electrons and further increasing absorption. Helium shield gas is more effective than argon in suppressing this effect because it cools the vapor plume and does not contribute many electrons itself.

Both pulsed and continuous-wave (CW) lasers are used for welding. To a first approximation, CW is used for speed, while pulsing is used for precision. Because keyhole welding is extremely non-linear, the irradiance must be high. If the workpiece is thin, very high travel speeds are required to keep the heat input low if the laser is on continuously. Pulsing the beam lets more reasonable speeds be used.

Joint geometries for laser welding

Because lasers are capable of producing thin, deep welds, it seems natural to select a butt joint configuration for laser welding. Figure 4, showing the outline of a laser weld over a butted seam, shows how well the weld shape matches the joint. Where butt joints are practical, they allow the greatest speed and the lowest heat input because all the metal in the weld is being used to hold the assembly together. In many cases, though, it's impossible to make a butt weld because the seam location is not controlled accurately enough. A lap joint (Figure 5) can often be used to increase the reliability of the welding process. Lap welds melt a lot of metal to produce a small connection, but they have a much larger tolerance on position than butt welds. Because laser welding is inherently fast and has a low heat input, a lap weld is often the most practical choice.

The spot sizes used in industrial laser welders range from about 0.1 to 1.0 mm, with 0.3 mm being a common size. Butt welds made with a 0.3 mm spot can miss the seam if they are more

than 0.1 mm out of position because the fusion zone becomes quite narrow near the bottom. The fusion zone can be widened some by going slower or using more power, but it is still hard to accommodate more than 0.2 mm of offset in a laser butt weld. The only requirement on a lap weld is that the laser hits the metal where both layers are in contact.

Regardless of the configuration, joint fitup is critical in laser welding. Almost all laser welds are autogenous: no filler metal is used. It is very difficult to get filler into the tiny melt zones that most lasers produce. With 10 kW or more, the melt pool gets bigger and easier to hit with a wire, but there are not too many lasers that powerful on production lines. So, any gaps in the joint become undercuts in the finished weld. Even if undercuts are acceptable, a focused beam can pass through a butt joint with a 0.2 mm gap without welding it at all; the beam just bounces off the walls and out the other side. The weld tooling must eliminate gaps between joint members and present the seam consistently to the laser beam. A rule of thumb for laser butt welding is the gap width should be no greater than 15% of the thickness of the thinnest section. Good tooling and accurate parts make for easy laser welding.

Materials for laser welding

Laser welds are like other welds only smaller. In most cases, there is no fundamental difference between laser welds and those made with conventional processes. There are, however, some points to consider.

First, laser welds, being small, cool very rapidly. If short-duration (less than 5-millisecond) spot welds are made on stainless steel, they can crack because of the high cooling rate. Increasing the pulse duration to 10 ms or longer usually cures this. When steel with more than 0.3% of carbon is laser welded, it transforms to martensite. This can produce a very hard and brittle weld, as well as a hard heat-affected zone (HAZ) next to the weld. High preheats or changing the material are the only ways to eliminate this problem.

The rapid cooling rate of laser welds has important benefits, too: There is very little chance for sensitization of stainless steel, and many metals have better mechanical properties when they are rapidly solidified. Heat-affected zones are small and distortion is minimal.

Next, lasers weld with light, so they have problems with reflective materials such as aluminum or copper. Aluminum, which has more commercial welding applications than copper, presents several metallurgical difficulties. Regardless of the welding process, most aluminum alloys must be welded with a filler metal having a different composition than the base metal to keep the welds from cracking. As mentioned before, filler metal is difficult to use with lasers. Additionally, some common alloying elements in aluminum (zinc and magnesium) have very high vapor pressures so they tend to boil out of the melt pool. Besides depleting the alloy content of the weld, this leads to keyhole instability and high levels of porosity in laser welds. A lot of work is being done to control the process, but laser welding of aluminum is fundamentally a touchy business.

Finally, the material being welded must be clean. This is a good idea for all welding, but more important for laser welding. Any non-metallic contaminants get ejected from the keyhole, producing spatter, undercut, porosity, and lens damage.

Conclusion

If you select the proper materials and joint configuration, and then make repeatable tooling, laser welding produces welds of the highest quality at production rates that cannot be matched by any other process. As a precision process, it requires care in its implementation and is intolerant of variations in joint fitup and location. It's a prime example of "do it right or do it over." As many manufacturers have learned, it's not that hard to do it right.

Leonard Migliore is president of Laser Kinetics Inc., a Mountain View, CA consulting firm. Contact 650-967-0977, (F) 650-967-1517, or info@laserk.com.

Archives Index | 1998 | July 1998 |